Design of 25kW Redundant Linear Electro-Mechanical Actuator for Thrust Vector Control Applications

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***Abstract*—Linear electro-mechanical actuators are finding increased use in the field of thrust vectoring of launch vehicles. Earlier, linear electro-hydraulic actuators were used especially in the lower stages of the launch vehicles where there is a requirement for large actuation forces. However, electro-mechanical actuators are being scrutinized for this purpose in an effort to provide lighter, cleaner and more reliant control actuators.**

The design philosophy, actuator configuration and selection of motor to meet the load dynamics, bearings, roller screw & sensor are discussed. Design verification of critical components like roller screw and rod end bearing assembly for their structural aspects is explained. Details of redundancy management scheme for the individual functional elements and the actuator qualification program are also covered.

Keywords—high power electromechanical actuator, redundancy management

I. INTRODUCTION

Electro-mechanical actuators (EMAs) are finding increased use in the field of Thrust Vector Control (TVC) of launch vehicles. In earlier days, electro-hydraulic actuators were used especially in the lower stages of the launch vehicles where there is a requirement for large actuation forces. Ensuring reliability, taking into account the large number of components as well as the high class of cleanliness required for electro-hydraulic actuators, has always been a challenge in the field of aerospace. Hence, electro-mechanical actuators are being scrutinized for this purpose in an effort to provide lighter, cleaner and more reliable control actuators.

The power of electro mechanical actuators was limited by the ability of drive electronics to handle the large electrical power, availability of high discharge light weight batteries and non-availability of high torque motors. The availability of high strength Samarium Cobalt magnets which have high coercivity and large operating temperature ranges have reduced the mass of magnet material required in a DC motor and permit a higher peak torque output for a given size. Advances in power electronics including development of Insulated Gate Bipolar Transistors (IGBT) with very low power loss across the switch have made it possible to build motor controllers for high power applications than was previously possible. The recent developments in Lithium ion batteries with high energy density have made usage of high current / power possible in launch vehicles.

A number of new generation launch vehicles like VEGA Launcher and H-IIA have started to utilize the potential of electromechanical actuators. Aerospace actuator manufacturers like M/s Moog Inc have realized that electro-hydraulic actuators will be replaced by electromechanical actuators in the near future and are currently developing high power electromechanical actuators to meet the demand [1]. Control actuators are safety–critical components of an aerospace system and an undetected actuator failure can lead to serious consequences. Any fault in the subassemblies of an EMA can be successfully and efficiently detected, identified and isolated using the limited set of sensor signals available [2].

II. SYSTEM CONFIGURATION

The engine gimbal control (EGC) system / thrust vector control (TVC) system for the launch vehicles consist of an actuator mounted to the engine at its one end and the other end attached on the stage. Engine will have one actuator for one plane (pitch or yaw) gimballing and will have two actuators for two plane gimballing (pitch and yaw). Two engines with two actuators mounted on each engine will provide three plane gimbal controls (pitch, yaw and roll). Fig. 1 shows the configuration of two plane engine gimbal control system.

The following are the specifications that have been used as design input for the design of electro mechanical actuator of thrust vector control system:

Max angular deflection, θ	:	6^o
10% system bandwidth, f	:	4 Hz

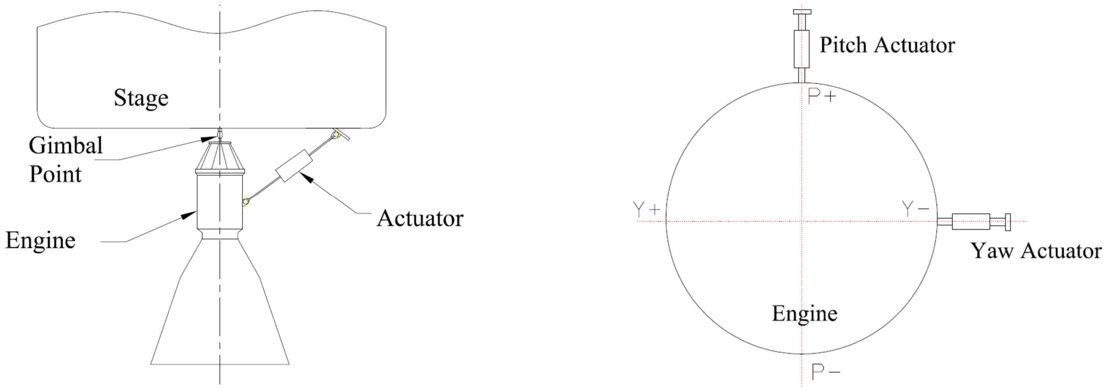

Fig. 1. Configuration of the Engine Gimbal Control System

Other parameters:

Engine Inertia, J_e	:	4000 kg-m^2
Control arm length, L	:	1100 mm

III. ACTUATOR CONFIGURATION

The actuator configuration consists of a housed 3 phase quadruplex brushless DC (BLDC) torque motor driving a roller screw through spur gear based compound gear train. The rotational motion of electrical motor/gear is transformed in the linear motion by constraining the rotational motion of the roller screw nut. The linear motion of roller screw nut is extended to the engine by piston which is rigidly connected to roller screw nut. A LVDT (Linear Variable Differential Transformer) sensor, with probe sliding inside the roller screw and being rigidly connected to the piston which follows the motion is used as the linear position feedback sensor to close the position control loop. Idler gear used between drive motor pinion and driven output gear provides the compactness to the actuator assembly. Deep groove ball bearings support the idler gear to handle the radial load imparted due to torque transmission. Angular contact ball bearings supporting the output gear will experience both radial and axial loads. Radial load are imparted by gear during torque transmission and axial load is due to the conversion of rotary to linear motion by roller screw. Fig. 2 shows the block diagram of typical electro mechanical actuator.

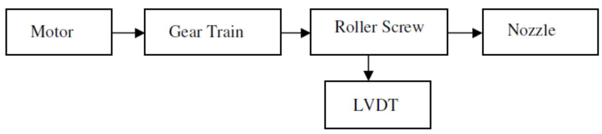

Fig. 2. Motion Transmission diagram for the EMA

After the optimal sizing of motor, the details of which will be discussed later, it is planned to operate the motor in current limiting mode with a supply voltage of 250 V and current being restricted to a maximum of 25A per coil. The linear position from LVDT is compared with a voltage equivalent to the desired displacement, command input to obtain the required engine angular position. The resulting error voltage is amplified, compensated and fed to the BLDC torque motor, which drives the roller screw/engine. The current loop ensures the desired current through the motor armature coils as per the reference control signal at the input of the current loop. Block diagram of typical electro mechanical actuator based TVC system is shown in Fig. 3.

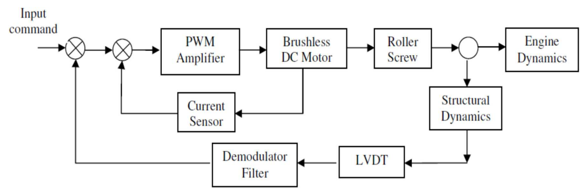

Fig. 3. Block diagram of typical EMA based TVC system

The mechanical housing and covers are configured with high strength aluminum alloys so as to minimize the weight of the actuator while still maintaining the required structural margins. The housing, with its high thermal mass, acts as an absorber of the internal heat generated by the motor coils. The gears and other structural members which have to withstand high loads are designed out of heat treated high strength stainless steel. All the aluminum components are anodized and the stainless steel components undergo passivation to ensure improved corrosion resistance.

Lubrication is provided to the gears and other moving elements by grease plating the components before assembly. Krytox grease based on perfluoropolyether oils is used since they can survive continuous high temperatures up to 260oC and provide exceptionally long life time. The connectors used for electrical connectivity of the actuator to the drive electronics belongs to high quality MIL-38999 III series. Both ends of actuators have rod ends with spherical bearings for connecting to the vehicle structure and nozzle which can handle fabrication/assembly misalignments if any.

IV. COMPONENT DESIGN AND REDUNDANCY SCHEME

The design of the redundant high power actuator has been based on the guideline that the launch vehicle mission should be able to tolerate any single failure and even two precedent failures should cause only a reduction in bandwidth of the actuator without causing a loss of control in the vehicle. The above said fault tolerant scheme has been implemented by incorporating redundancy in all the electrical elements like electric motor and position feedback sensors.

A. BLDC Motor

In order to achieve the required redundancy, a quadruplex brushless DC torque motor was chosen. This four channel motor has its rotor comprised of Samarium Cobalt magnets and a stator with four star connected three phase windings arranged in separate quadrants around the periphery. The physical separation of the stator coils ensure that the chances of failure of one coil propagating to the adjacent coils are kept to a minimum. Here, each of the windings will act as an individual motor whose torque will be electromagnetically summed along with other windings on to the rotor. This configuration has been found to be more reliable than using multiple motors and obtaining the torque summing with the help of gears [3]. Fault detection of the coils is done by cross comparison of coil currents. When a deviation beyond the threshold value is observed, the failed coil is identified and isolated since such a coil can offer resistive torque by working as a generator.

For commutation of the motors, Hall Effect sensors are used. Three Hall Effect sensors separated by an electrical angle of 120o is required for proper switching of the windings. For redundancy purpose, three such sets are provided. A failure in the Hall Effect sensor set can be identified by comparison of command given to the system and its response. Additionally, one resistance temperature detector is bonded to the outer surface of the stator to have a continuous motor temperature monitoring.

TABLE I. SPECIFICATION OF TORQUE SENSOR

Peak torque	70 Nm (with 4 coils,100A) 52 Nm (with 3 coils, 75A)
Peak current	25A per coil (Total = 100A)
Supply voltage	250V (nominal)
No load speed	3400 rpm @ 250 V
Weight	10 kg
Dimensions	ø150 x 175 mm

The torque and speed of selected torque motor to meet the actuator bandwidth is checked by the load locus studies. The actuation torque requirement is specified with respect to the engine gimbal point. The major load torque components to be met by the actuator are:

(i) Inertial Torque

Inertial torque is caused due to the acceleration of the rotating members whose inertia includes the mass moment of inertia (M.I) of the engine as well as the inertia of the rotor reflected to the actuator end.

$$T_i = (J_e + J_r)\,\ddot{\theta}_E$$

Where, the reflected M.I of the rotor on the actuator end J_r is

$$J_r = J_m\left(\frac{2\pi L}{p}\,G\right)^2$$

Where, J_e is the engine inertia estimated as 4500 kg-m^2,
J_m is the rotor inertia estimated as 2.7 x 10^{-3} kg-m^2
L is the actuator lever arm of 1100 mm
p is the lead of the roller screw estimated as 10mm
$\ddot{\theta}_E$ is the acceleration of engine (assumption: engine movement is sinusoidal) and
G is the gear ratio between motor and roller screw, taken as 2.

(ii) Coulomb Friction Torque

The Coulomb friction torque of the gimbal bearing, $\mathbf{T_C}$ that will be encountered by the actuator was estimated to be 4000 Nm. In comparison to Coulomb friction, viscous friction at gimbal joint at low velocities was found to be negligible and hence was neglected.

(iii) Engine Thrust Offset Torque

$$T_o = T\,\varepsilon$$

Where, T is the thrust of the engine given as 4,000 kN and
ε is the maximum expected engine thrust offset, estimated as 5 mm.

(iv) Disturbance Torque

Disturbance torque occurs due to the disturbances created by the lateral and linear accelerations of the vehicle

$$T_d = MI_e\ddot{x}\theta_E - MI_e\ddot{z}$$

Where, I_e is distance between the gimbal joint and centre of gravity of the engine, estimated as 1100 mm,
M is the mass of the engine, taken as 3000 kg,
$\ddot{x}$ and $\ddot{z}$ are the linear and lateral accelerations , estimated as 30 m/s2 and 5 m/s2 respectively.

Total load torque can be given as

$$T_e = T_i + T_C + T_o + T_d$$

Converting the total load torque to motor torque,

$$T_m = \frac{T_e}{n}$$

where n is the ratio of motor speed to engine speed

$$n = \frac{2\pi L}{p}\,G$$

Translating the engine torque and speed requirements to motor, it becomes as –

$$\dot{\theta}_M = \dot{\theta}_E\,n$$

$$T_m = \{(J_e + J_r)\,\ddot{\theta}_E + T_C + T\,\varepsilon + MI_e\ddot{x}\theta_E - MI_e\ddot{z}\}/n$$

Using the above two equations, the load locus for torque and speed requirement of motor is plotted for a

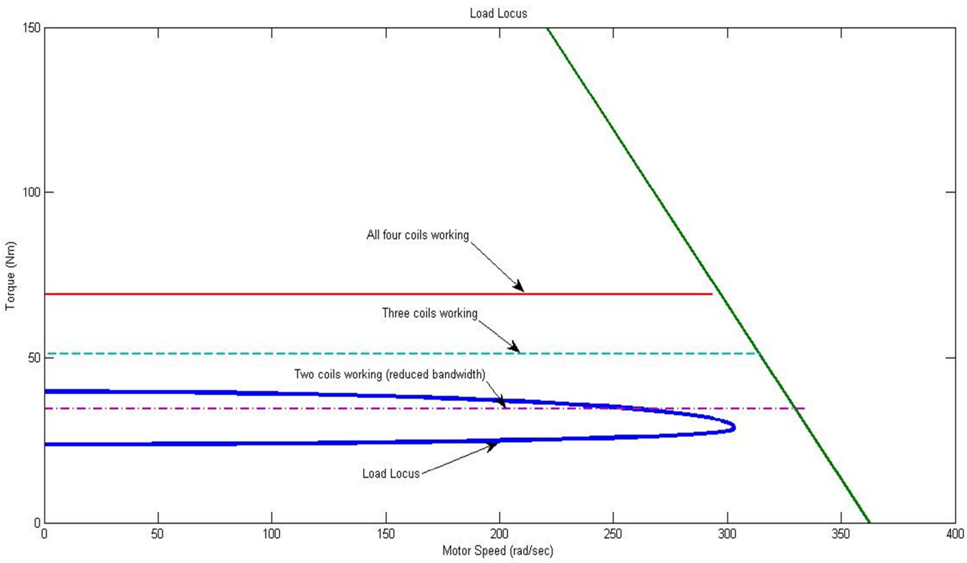

Fig. 4. Load locus plot

sinusoidal motion of engine with 10% amplitude (of 6o) at a frequency of 4 Hz. Fig. 4 shows the load locus plot.

It was estimated from the load locus studies that with four coils of the motor in working condition, a bandwidth of 6.2 Hz can be met without any margins. In the event of a coil failure, i.e. with 3 coils working a bandwidth of nearly 5 Hz can be obtained, demonstrating margins over the system bandwidth requirement of 4 Hz. In a scenario where two coils of the motor has failed, a reduced bandwidth of 3.2 Hz can be obtained, which will be sufficient to salvage the launch vehicle mission even though the system requirements will not be fully met. Hence, from the above load locus studies, it is confirmed that the motor torque and speed specification will meet the actuator bandwidth requirements.

B. LVDT

A triplex LVDT is used as the position feedback sensor. Operation of LVDT does not require electrical contact between the moving part (probe or core rod assembly) and the transformer, thereby ensuring higher reliability under severe working conditions. This ratio metric LVDT has three independent sets of windings and probes attached to a common adaptor. A majority voting logic is used among the three channels for identifying the correct signal to be used for feedback purposes. The outputs of each channel are independently available and are used for sum voltage monitoring to ensure failure detection. Also, by designing the signal conditioning electronic circuitry to measure the difference over sum ratio, the temperature coefficient of sensitivity can be dramatically reduced as well.

TABLE II. SPECIFICATION OF LVDT

Type	Triplex, Ratiometric, AC/AC
Electrical stroke	± 175 mm
Mechanical stroke	± 177 mm
Excitation voltage	7 V_{rms}
Excitation frequency	Channel 1: 2900 ± 50Hz Channel 2: 3100 ± 50 Hz Channel 3: 3300 ± 50 Hz
Size	Ø 28 x 710 mm

C. Roller Screw

The planetary roller screw comprises of a threaded screw shaft with multiple starts of thread, a nut equipped with the same number of starts of an identical profile and a set of at least 3 rollers which are threaded with a single start of thread having angle matching the nut thread. The rollers when they freely roll inside the nut follow a planetary path and do not move axially, thereby ensuring that there is no need for any recirculation. To eliminate backlash and improve axial rigidity, double nut with spacer in between is provided to facilitate preloading.

There are several potential failure modes that can be identified for the roller screw. Seizure of the roller screw mechanism preventing motion of the actuator at an inopportune time can be catastrophic. The strategy for dealing with such failure modes was to provide adequate torque to overcome some degree of potential mechanism seizure. It has been asserted by the manufacturer that small scale deformation, wear, as well as any potential hazard of contamination, would likely result in only degraded actuator performance and not failure. Any foreign material will not penetrate a properly shielded and covered roller screw. Since the screw is encapsulated inside the housing, which converts rotary motion to linear motion, no possibility exists for introduction of large foreign particles. Smaller speck of foreign matter will not damage the roller nut and will traverse and exit the nut in a short period of time [4].

TABLE III. SPECIFICATION OF ROLLER SCREW

Type	Double nut planetary with accuracy grade of G3
Material	X 40 Cr Mo VN 16-2
Lead	10 mm
No. of rollers	5 per nut
Dynamic load rating	186 kN
Static load carrying capacity	390 kN
Maximum allowable speed	2700 RPM
Size of nut, screw	Ø152 x 125 mm; Ø60 x 400 mm
Buckling load capacity	1335 kN
FoS on axial load	11

D. Gear Train

A simple spur gear based compound gear train of gear ratio 2 with one idler configuration to have compact size was chosen. This configuration was found to be optimal in minimizing the effect of gear inertia / reflected inertia load on the motor. Involute profiled spur gear parameters have been finalized based on the bending fatigue failure criteria using Lewis equation with maximum torque at the time of stalling taken as the load. The fabrication of gears is made conforming to DIN 6 Class with ground surface finish. This quality class along with stringent control over the gear centre to centre distances minimizes the introduction of backlash and other nonlinearities to the system.

TABLE IV. SPECIFICATION OF GEAR TRAIN

Parameters	Pinion	Idler	Gear
Type	Spur gear with involute profile		
Material	17-4 PH (H 1025 condition)		
Pressure angle	20^o		
Quality class	DIN 6		
No. of teeth	33	51	66
Module	3	3	3
Pitch circle diameter	99	153	198
Addendum	1 x module		
Deddendum	1.25 x module		
Factor of safety in bending stress	7.5	10	7

E. Piston

The piston is used for transmitting motion of the nut into final output stroke of the actuator. It is partly hollow to accommodate the screw of the roller screw and has the rod end bearing attached to its end.

TABLE V. SPECIFICATION OF PISTON

Material	17-5 PH Steel (H1025 condition)
Overall Size	Ø75 x Ø65 x 425 mm
Buckling load capacity	1080 kN
FoS against buckling	11

F. Ball Bearings

Single row deep groove ball bearings (4Nos; 2Nos each on one side) and single row angular contact ball bearings (4Nos; 2Nos each on one side) were selected for the assembly. The bearings were chosen so as to conform to ABEC 7 Class and were also analyzed for their static and dynamic load carrying capacity. The angular contact ball bearings are preloaded externally so as to make the required contact angle.

TABLE VI. SPECIFICATION OF ANGULAR CONTACT BALL BEARING

Type	Single row angular contact
Contact Angle	30^o
Static load rating	75 kN
Dynamic load rating	85 kN
Dimensions	Ø80 x Ø140 x 26
Factor of safety	6

TABLE VII. SPECIFICATION OF DEEP GROOVE BALL BEARINGS

Type	Single row deep groove
Static load rating	5 kN
Dynamic load rating	4 kN
Dimensions	Ø40 x Ø52 x 7
Factor of safety	9

G. Rod end bearing

Spherical rod end bearings are provided at the mounting ends of the actuator to provide flexibility in movement of the actuator. The rod end bearings have been chosen so as to have sufficient margins in radial loads that will be encountered during the actuator duty cycle.

TABLE VIII. SPECIFICATION OF ROD END BEARING

Type	Fraslip-E (MIL-B-81820)
Material	17-4 PH steel
Static radial limit load	585 kN
Factor of safety	6
Weight	2.3 kg

H. Connector

The connectors used for electrical interfacing of the actuators belong to high quality MIL-38999 III series. Two separate connectors are provided for power and sensor cables so as to prevent cross talk and noise susceptibility. All electrical connections terminated to the connector are made double at the connector end by using a U hook joint. This ensures that even on losing one electrical contact at the mating connector side, the

electrical integrity of the whole system remains uncompromised.

TABLE IX. SPECIFICATION OF CONNECTOR

Type	Circular connectors (Space grade)
Standard	38999 Series III
Shell style	Wall mount receptacle
Class	Nickel plated stainless steel

I. Structural Members

Mechanical and structural faults are likely to be the main source of concern for electro-mechanical actuators deployed in the demanding conditions of aerospace applications. Their main causes are excessive loads, environmental factors, lubrication issues, and manufacturing defects. Providing redundancy on structural members is a complex problem involving addition of new members which may in turn reduce the overall reliability of the system unless immense care is taken. All margins of safety were computed against an endurance limit for 20,000 cycles for the corresponding material to ensure adequate protection against fatigue failure.

Additionally, in order to ensure the health of the gear box assembly and other rotating members, accelerometers are mounted on the body of the actuator during the testing of actuator. The output of the accelerometers are used for component health monitoring by using Fast Fourier Transforms and statistical waveform analysis techniques like crest factor / kurtosis computation and comparison.

J. Battery Configuration

Batteries are the power source for electro mechanical actuators. Optimal selection and configuration of batteries can lead to significant savings in the overall weight of the system. Lithium ion batteries have been selected for use in this configuration mainly due to their ability to handle large currents and higher energy density when compared to Silver Zinc batteries which are normally used in launch vehicles. The weight reduction on batteries obtained by this selection is nearly 30%.

Each coil of the BLDC motor can demand a maximum of 25 A, but for a short duration only. After taking into account the power demand of an actuator undergoing a typical flight duty cycle, the configurations that can be used were found to be either two 80 AH batteries or four 40AH batteries. Four 40 AH batteries were selected and connected in such a way that each battery is powering one coil of the motor. Hence, in case of a battery failure, each motor will still have three healthy coils which can cater to the supply of adequate control force and ensure a successful mission.

V. ACTUATOR SPECIFICATION

Using commercial ACAD software, the actuator assembly was carried out with the selected components for the compact size and minimum unused volume. The actuator assembly is shown in Fig 5.

TABLE X. SPECIFICATION OF DESIGNED ACTUATOR

Parameters	Value
Stall force	96 kN
10% Bandwidth	6.2 Hz
Electrical working range	165 mm
Mechanical working range	175 mm
No load speed	41 mm / s
Power input	250 V, 100 A
Size	386 x 483 x 937 mm
Mass estimated	55 kg

VI. TEST METHODOLOGY

The actuator has to be subjected to a number of performance evaluation tests which simulate the worst case scenarios that will be seen by the actuator preflight as well as during flight. The tests will include performance characterization under standard room conditions as well as environmental testing.

The actuator will undergo two different sets of tests depending on the requirements- qualification tests or acceptance tests. Design Qualification Tests (DQT) are design verification tests to demonstrate the capability of the actuator to withstand the service conditions with specified margins of safety. The tests are intended to uncover deficiencies in design & the manufacturing methods and demonstrate the design margins. Flight Acceptance Tests (FAT) are performance verification tests on flight components/subassemblies. The specification for the above test is drawn in such a way that if the actuator successfully undergo these tests, one can expect with satisfactory level of confidence that the actuator will perform as per design during the flight. The test levels are the levels that are the maximum expected during flight and of duration equal to service condition, or minimum required for uncovering the workmanship errors whichever is higher.

A. Standard Room Condition Tests

These tests done at room conditions include electrical checks, time domain performance analysis by means of step response, frequency domain performance analysis using bode plots, stall force capability, starting friction, backlash, scale factor verification, FDI capabilities and linearity tests.

B. Vibration and Shock Tests

A sinusoidal vibration test is carried out to assess the capabilities of actuator and its subsystems under periodic transient excitations caused by instabilities like POGO and transients due to staging, oscillating pressure, engine

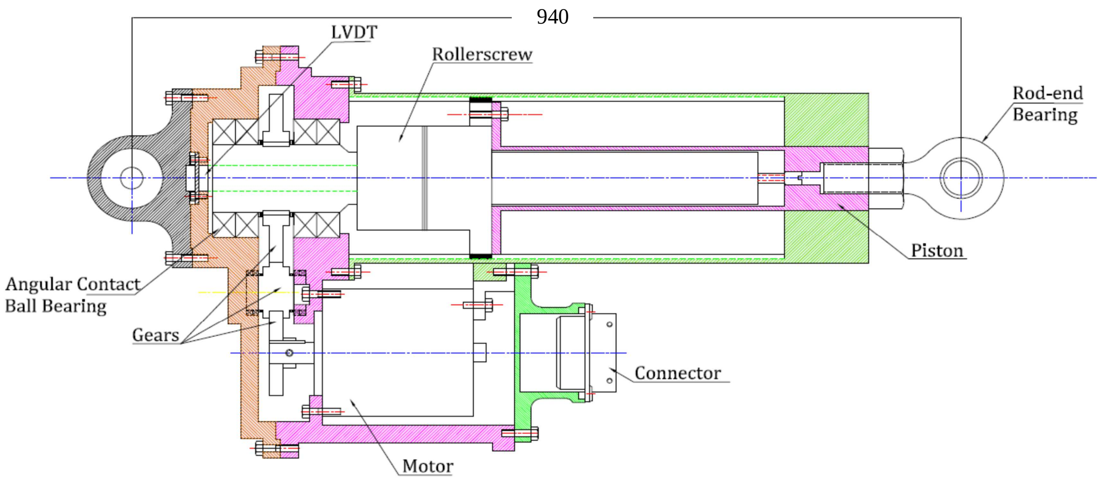

Fig. 5. Actuator assembly

ignition and shut off. The vibration shall be carried out in all the three axes with the specified levels. Random vibration tests are intended to demonstrate the ruggedness of the actuator and its components under high frequency excitations due to acoustics.

Shock test is intended to verify the sustenance of the actuator and its components to mechanical shocks by applying simple reproducible impulsive acceleration with the help of a vibration shaker. Sine vibration and shock tests are performed during DQT only.

C. Thermal Tests

Thermal tests are tests which demonstrate the ability of the design to withstand the environment that might be encountered during shipment, storage or flight. A dry heat test conducted for a minimum of 5 hours verifies the influence of the variation of dielectric properties, thermal expansion etc. on the performance of the actuator. The cold soak test is done to verify that the design ensures performance under extreme thermal conditions to which the components are likely to be exposed during their lifetime.

D. Humidity and Water Proof Tests

Humidity test is carried out to assess the resistance of the component to high humidity conditions and variation of temperature cycle associated with humid conditions encountered in tropical areas, particularly, those at the launch site. The waterproof test is carried out to verify the performance of the components when exposed to rain. Both the tests are conducted as per IS 8252.

E. Vacuum Test

Vacuum test is carried out to verify the performance and capability of components to function during and/or after subjecting them to the hard vacuum condition. The vacuum test uncovers the phenomena like failure of insulation during the pressure between 10 to 10-4 mbar, the effect of corona discharge at low pressures and swelling of the material.

F. Electromagnetic Compatibility

The qualification actuator undergoes the Electromagnetic compatibility tests in accordance with the MIL specifications including MIL-STD-461/462 including RS02 and CE02 tests.

VII. Conclusion

The selection of quadruplex motor to meet the load torque and speed requirements using load locus studies was described in detail. The motor chosen meet the actuator bandwidth requirement even with one failure as per redundancy requirement. Redundancy methodology of motor, LVDT was explained. Design / selection criteria of machine elements viz, gears, rollerscrew, ball bearings, rod end bearings, ete were discussed. Actuator designed can develop a stall torque of 96.7 kN. Test methodology of actuator was also explained in brief. Finite element analysis of critical components like piston, gears, rollerscrew, etc and the actuator realization are planned as future scope of work.

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